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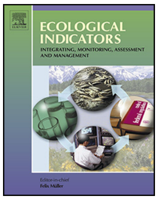

Original articles

The influence of landscape pattern on the risk of urban water-logging and flood disaster

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ABSTRACT

Most Chinese cities face a series of 'urban diseases' or problems during rapid urbanization, and of which urban precipitation and subsequent water-logging is a severe hotspot. A better understanding of the influence of urban land-use patterns on water-logging will be helpful for enhancing urban flood resistance. The relationship between the characteristics of land-use patterns and the risk of urban water-logging and flood disaster (UWLFD) was analyzed in this paper, using landscape pattern indicators to describe the land-use structure. These included patch density (PD), edge density (ED), landscape division index (DIVISION), contagion (CONTAG), Shannon's evenness index (SHEI), and Shannon's diversity index (SHDI). The risk of UWLFD was measured using the topographic slope and urban surface cover. Based on GIS and remote sensing data in 2003 and 2013, a case study of the metropolitan region of Kunming City showed that the risk of UWLFD had a positive correlation with landscape fragmentation (e.g., PD and ED), and strong negative correlation with landscape contagion (e.g., CONTAG) during the study period. This implied that landscape fragmentation aggravated the risk of UWLFD while landscape connectivity reduced the risk. Measures such as unified and long-term urban planning and design and the construction of green infrastructure will reduce the risk of UWLFD. The relationship between the landscape pattern and the risk of UWLFD provides a new perspective for systematic urban planning.

1. Introduction

During the process of rapid urbanization, a series of 'urban diseases' has emerged in China, among which floods and subsequent water-logging following rainstorms are serious problems (Weng, 2001; Cai et al., 2011c; Chen et al., 2015). When water-logging and floods happen, urban socio-economic activity is interrupted with economic losses and destruction of urban life support systems, including transportation, communication and supplies of water, electricity, and gas (Grove and Harbor, 2001; Cai et al., 2011a). It was reported that 62% of Chinese cities experienced water-logging and flood disasters during 2008–2010, and 137 cities experienced these more than three times during that period (Wang et al., 2012). Increasing attention has been paid to urban floods in China especially after the Beijing flood disaster on 21 July 2012 when floodwaters killed 79 people, destroyed 8200 homes and caused over US$1.6 billion in damages (Huang, 2012).

It is evident that UWLFD are becoming more frequent and serious with urbanization. There are two main reasons. On the one hand, urban sprawl changes the original geomorphology and thus the natural hydrological cycle among atmosphere-hydrosphere-lithosphere-biosphere, consequently decreasing the ability to store water (Ramotra et al., 2015). On the other hand, the increase of impermeable surfaces reduces drainage ability (Ren et al., 2014). To mitigate water-logging and subsequent damage, it is helpful to understand the relationship with the two basic causes, which are both related to the change in urban land-use patterns. Landscape pattern can be an effective analysis tool for UWLFD, because it links theoretical analysis and practical change, and integrates multiple characteristics of land-use change (Peng et al., 2015; Fernandes et al., 2016).

Various studies have been conducted into UWLFD, which can be divided into three aspects. First, the risk of water-logging disasters has been evaluated based on indicators, historical disasters and scenario simulation (Quan, 2012; Tramblay et al., 2014; Alfieri

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et al., 2015; Falter et al., 2015; Foudi et al., 2015). Second, the causes of urban water-logging disasters have been analyzed, e.g., the poor design and insufficient maintenance of urban water discharge systems, the reduced amount of rain penetration into soil due to lack of green infrastructure, and the soft soil and subsidence caused by urban sprawl (Al-Sabhan et al., 2003; Butler and Pidgeon, 2011; Ran and Zorica Nedovic-Budic, 2016). Third, investigation into mitigation measures has been carried out (Alphen and Lodder, 2006; Werritty, 2006; Grabs et al., 2007; Cai et al., 2011b; Rouillard et al., 2014). For instance, low-lying urban areas are converted into parks and green land in Germany, so they can also regulate floods when necessary. In the Netherlands, all pools and underground pipes are designed as a recycling network (Chen, 2012). Despite these approaches, it is valuable to analyze UWLFD from the point of view of changing urban patterns, e.g., using the tool of landscape pattern analysis which has been widely applied in urban green space analysis (Tian et al., 2014), environmental factor analysis (Chen, 2012), watershed pollution control (Weber et al., 2006) and urban heat islands (Chen et al., 2014).

We used landscape pattern analysis to study UWLFD in this paper, and analyzed the influence of landscape pattern on the risk of UWLFD. Using Kunming—the sole mega-city in Yunnan Province and the third largest city in southwestern China—as a case study, we also analyzed the main causes of urban floods, as well as possible mitigation measures.

2. Methodology

2.1. Basic analysis procedure

As shown in Fig. 1, four steps were used to analyze the relationship between landscape pattern and the risk of UWLFD, i.e., data collection, data processing, indicator calculation and results analysis.

First, the base data was collected, e.g., Landsat TM remote sensing images and a DEM. Second, the data was processed to acquire some key indicators, e.g., change of urban land-use pattern during the study period, topographic slope values and urban surface coverage. Third, calculations were made to obtain the important indicators, i.e., the landscape pattern indicators and the risk value of UWLFD. Finally, correlation analysis was conducted to check the relationship between the two aspects, and suggestions were proposed to reduce the risk of UWLFD. More details are given in the following sections.

2.2. Indicator calculations

2.2.1. Urban landscape pattern indicators

Landscape pattern indicators are widely applied to describe changes in landscape structure. Six indicators shown in Table 1 were selected in this paper to meet the study goal, based on previous research. The map of land-use categories was transformed to a 30 m × 30 m grid by using ArcGIS 10.2, and from this the six landscape pattern metrics were quantified using FRAGSTATS 4.2.

We extracted the values of landscape metrics by moving overlapping windows on some typical transects. This provided an assessment of the spatial distribution of the landscape metrics, allowing gradual changes of urban landscape pattern to be represented.

2.2.2. Risk of UWLFD

The risk of UWLFD is closely related to natural and human factors. Natural factors usually include climate, altitude, slope, soil, and vegetation. Human factors include urbanization and urban construction, during which the urban surface cover is changed (e.g., impermeable land greatly increases) which affects urban drainage systems. The risk of UWLFD can be measured as follows:

$$Q = \omega_n Q_n + \omega_h Q_h = \omega_n \sum \omega_{ni} Q_{ni} + \omega_h \sum \omega_{hj} Q_{hj} \qquad (1)$$

where Q is the integrated risk of UWLFD, Q_n is the risk of UWLFD caused by natural factors, ω_n is the weight of Q_n, Q_h is the risk of UWLFD caused by human factors, ω_h is the weight of Q_h, Q_{ni} is the risk of UWLFD caused by the ith natural factor, ω_{ni} is the weight of Q_{ni} among all natural factors, Q_{hj} is the risk of UWLFD caused by the jth human factor, and ω_{hj} is the weight of Q_{hj} among all human factors.

Considering the characteristics of the study area and the available data, topographic slope and surface cover were selected to express the natural and human factors, respectively. The grids of the slope distribution were calculated from the 30 m × 30 m DEM data of the study area, and then the topographic slope was classified into 15 classes using the natural breaks method. Values were assigned to the 15 classes with area with higher values having a greater risk of UWLFD. To obtain the risk of UWLFD from different surface covers, the study area was classified according to the resistance of different land cover types toward water-logging (Sun, 2014), e.g., a water body can effectively mitigate the water-logging hazard and collect the water runoff, grassland, forests and agriculture land can help slow down storm water runoff, and impervious construction land can increase the peak rate and runoff volume. Different values were assigned to different classes, where areas with higher values had a greater risk of UWLFD. The higher value meant the land-use type was more vulnerable to the water-logging hazard. Finally, an even weight was applied to generate an integrated risk of UWLFD, i.e., the weights of natural and human factors were both set at 0.5.

2.3. Study area

Kunming City is the only mega-city in Yunnan Province and the third largest city in southwestern China. As the leader of the urban economic circle in Middle Yunnan with a fast-growing economy, its development is significant for constructing a new economic belt in China. However, Kunming is prone to UWLFD due to its abundant summer rainfall. It is believed that Kunming will be a representative case study area for this analysis. As shown in Fig. 2, the study area includes the main urban areas (Panlong District, Wuhua District, Xishan District, and Guandu District), Chenggong County, and Jinning County, which surround Lake Dian, the largest plateau lake in Yunnan Province.

2.4. Data sources

The Landsat TM remote sensing images of Kunming in different years were downloaded from the Geospatial Data Cloud (Computer Network Information Center, Chinese Academy of Science, 2016) and the clearer images in 2003 and 2013 were selected as the foundation data. All remote sensing images were projected in WGS-84 coordinates. The DEM data were downloaded from the ASTER GDEM database with resolution of 30 m.

3. Results

3.1. Urban landscape pattern indicators

As indicated in Table 2, all fragmentation indicators (i.e., PD, ED, and DIVISION) increased during the study period. This suggested that patches were further divided by human disturbance, which increased landscape fragmentation. According to the diver-

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